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B-H Curves of Some Magnetic Material for Temperature Compensation

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Abstract

Measurements of the magnetic properties of a selection of temperature compensator magnetic materials has been carried out using a simple apparatus based on a large magnet and a pair of Hall Probes. Results of measurements for a selection of materials is presented with an emphasis on various metallic Fe-Ni products.

1 Introduction

The Recycler Ring Project is exploring the use of Hybrid Permanent Magnets for a storage ring. To provide a constant field strength in the face of a temperature coefficient of -0.2%/K in the driving field from the Strontium Ferrite bricks, consideration has been given for using a magnetic temperature compensation[1] Design of such a compensator requires knowledge of the magnetic properties of compensator materials and the temperature dependence of these properties.

Available data on these materials is typically limited to measurements at low fields (top fields from $50 - 300\ Oe$ are typical). It is believed that a suitable magnetic circuit for recycler ring application may involve using them at $> 1000\ Oe$. To provide suitable data for design calculations we have chosen a simple system which will permit us to make measurements quickly with limited but adequate precision.

2 Test Apparatus

Using a box of cold rolled steel separated by aluminum spacers, we create two uniform field regions. One has the gap spacing of the box. The other has that gap reduced by the introduction of magnetic materials under test. We measure in the center of areas which are large enough compared to the gap spacing that we assume uniform fields. Figure 1 illustrates this assembly.

The gap built into the fixture as determined by the aluminum side rails is 1.00". With materials for which we have adequate samples, we have created a 3" x 6" stack, so even with a 1" gap the center of the stack is at least 1.5 gap heights from the edge, assuring an adequately uniform field. The material available initially from Carpenter Technologies is so small that the stack which can be created is small enough that the field is apparently not sufficiently uniform, as indicated by the failure of the simple analysis to produce good intercomparison among results with different stack heights.

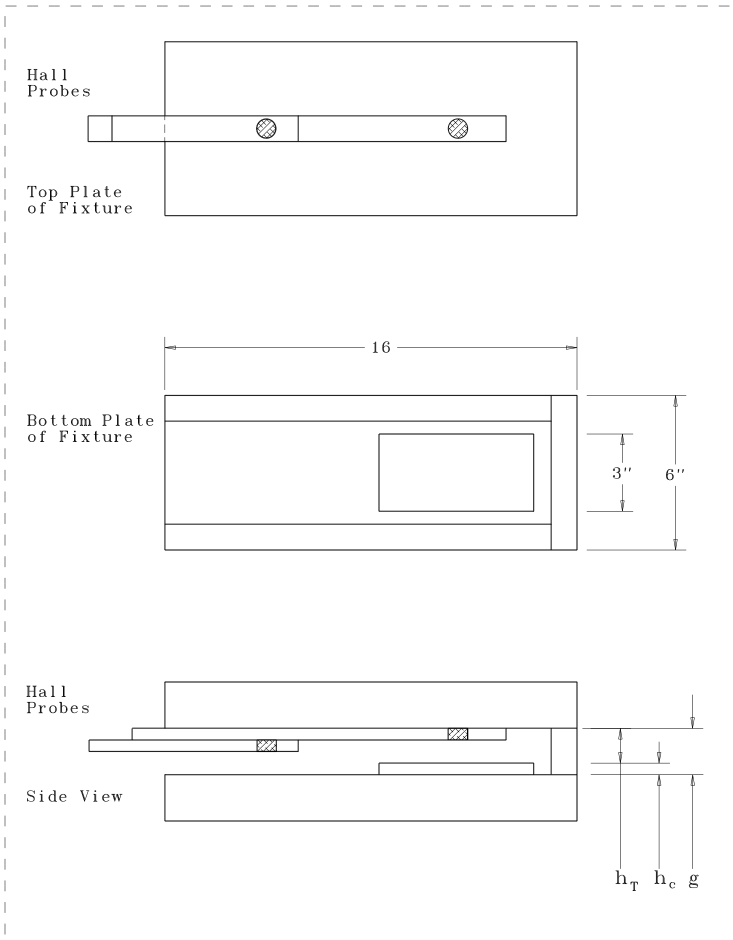


Figure 1: Test Fixture for Compensator Tests. Entire device is placed in the uniform dipole field of an electromagnet with field direction across the gap g.

As a result, we have performed additional tests in which a 1/4” x 3” x 13” piece of steel was inserted on the bottom plate, below all other materials, reducing the gap g to 0.75” and making h_T and h_c smaller. This also makes the gaps smaller compared with the stack width and length. A larger sample from Carpenter Technologies has also been received and tested.

Measurements with this device open to the air provide suitable room temperature measurements. By wrapping the fixture with electric heater tapes and enclosing it in fiberglass insulation, we are able to make measurements at well controlled temperatures substantially above room temperature.

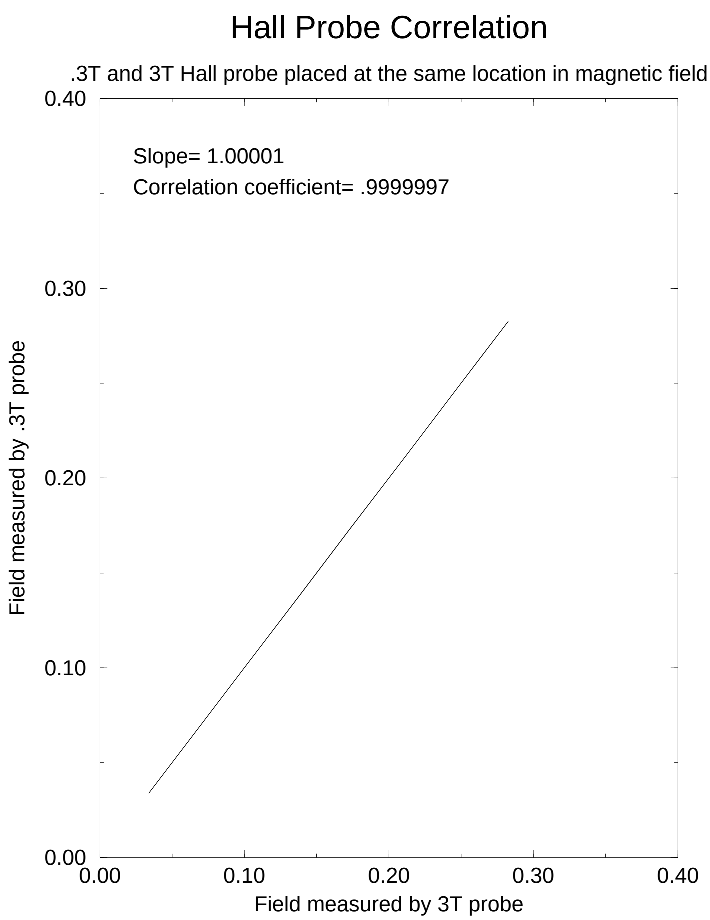
The Hall Probes used are two models of Group 3 Hall Precision Digital Teslameter. Each is read with a DTM-141-DG meter. Model LPT-141-7 probe has a top field of 3 T, Model LPT-231-7 has a higher resolution but a maximum field of 0.3 T. As shown below, the cross calibration of these probes is fundamental to the precision of this measurement. To confirm the the response of the probes, we arranged them one above the other and recorded the measured fields at many field levels (power supply currents). Figure 2 shows the correlation plot for these measurement with the fitted slope and correlation parameters as determined by XMGR. This confirms that no further correction of the probe data is required.

Sample #	Manufacturer	Type	Width inches	Length inches	Height inches
1	Sumitomo	MS1	1	6	0.0398
2	Sumitomo	MS3	1	6	0.0401
3	Arch Metals		1	4	0.0506
4	Carpenter	TC30 Type 4	0.4375	4	0.0451
5	Carpenter	TC30 Type 4	1	6	0.0509
6	Castle Metals	Monel 400	1	3	0.0613

Table 1: List of products tested as temperature compensation materials.

3 Samples Available for Testing

Samples of metallic compensator materials have been received from a number of vendors. A list is shown in Table 1. An initial sample from Carpenter Technologies is very small and required special efforts for testing. A much larger order of material from the same source has now been tested. A sample has come from Arch Metals. Two samples from Sumitomo Metals are available in quantity. They are designated as types MS1 and MS3. All of the above mentioned materials are Fe-Ni alloys with about 30% Ni with perhaps small additions of other materials. In addition, we are able to make



probe_correlation.gr

Figure 2: Calibration of the two Hall Probes used for this measurement is confirmed in this measurement in which one is placed above the other in the gap.

measurements using Monel[1], which is a Cu-Ni alloy with a composition not grossly different from materials which have previously been reported as useful for thermal flux compensation[2].[2]

[1]The sample tested was purchased as Monel Alloy 400. The certification certificate indicates Ni 64.85%, Cu 32.27%, Fe 1.54%, Mn 1.00% with traces of Al, C, and Si.

[2]Data is provided by Kinnard and Faus on an alloy with Ni 66.5%, Cu 30% and Fe 2.2%.

4 Data Collection and Analysis

The data for this measurement is recorded using a program running on a VME-based computer under Unix (SunOS). After querying the operator for equipment and sample identifications, it controls the current in the magnetizing magnet (upon operator request) and after each current change, records the temperature, field at each Hall Probe, current and time. This data is stored in an ASCII file. Further analysis is carried out using a 2020 Spreadsheet program and XMGR plotting packages.

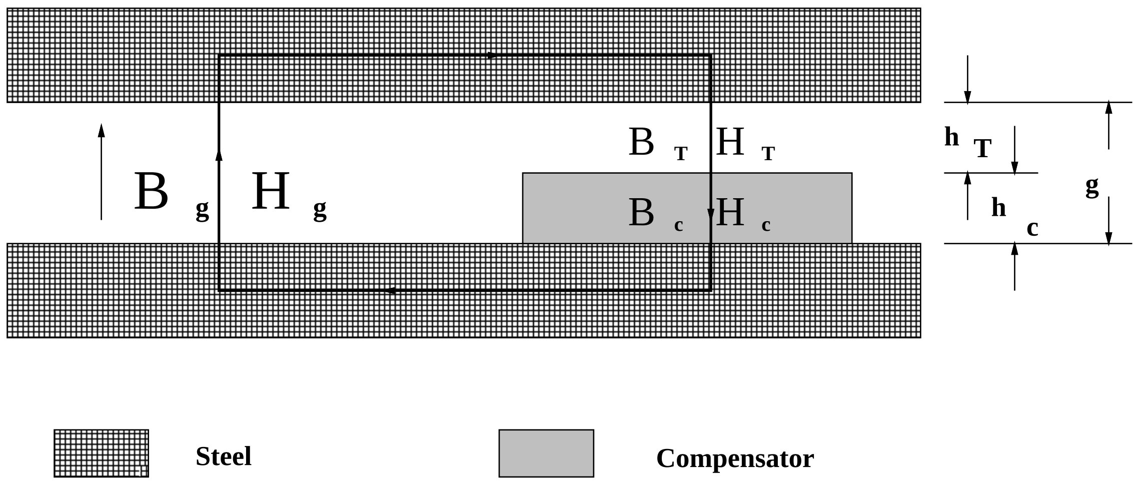


Figure 3: The test apparatus is illustrated to show the magnetic circuit. B and H are identified at each point. The path used for applying Ampere's Law is shown. The gaps g and h_T are air gaps.

In Figure 3 we see the variables which are measured and analyzed. The Hall probes measure B_g and B_T. If we take the convention that B and H point up in the gap, we can apply Ampere's Law around the path shown, integrating H on the vertical paths and noting that H is perpendicular to the path where the path is horizonal. Thus

$$\int H \, d\ell = 0 = \frac{B_g g}{\mu_0} - \frac{B_T h_T}{\mu_0} - H_c h_c \tag{1}$$

Solving for H_c we find

$$\mu_0 H_c = \frac{B_g g - B_T h_T}{h_c} \tag{2}$$

Applying flux conservation across the boundary between the compensator and the gap h_T implies

$$B_c = B_T \tag{3}$$

Using this pair of equations, we solve for the fields in the compensator using measured quantities.

Further insight into the limitations of the measurement can be obtained with further manipulations. We note that $h_T = g - h_c$ and we apply this to Equation 2, finding

$$\mu_0 H_c = B_T - (B_T - B_g)\frac{g}{h_c} \tag{4}$$

or

$$\mu_0 H_c = B_g - (B_T - B_g)(\frac{g}{h_c} - 1). \tag{5}$$

We also note that the magnetization $\mu_0 M = B - \mu_0 H$ is simply

$$\mu_0 M_c = (B_T - B_g)\frac{g}{h_c} \tag{6}$$

The configurations tested are shown in Table 2. Using different configurations, we confirm the usefulness of the above simple analysis. Further testing then proceeded to permit temperature dependent studies.

Test Date	Sample #	Number in stack	gap inches	h_c inches	h_T inches
07/31/95	1	5	1	0.199	0.801
07/31/95	1	5	1	0.199	0.801
07/31/95	1	10	1	0.398	0.602
07/31/95	4	4	1	0.1804	0.8196
07/31/95	4	3	1	0.1353	0.8647
07/31/95	2	10	1	0.401	0.599
08/01/95	2	5	1	0.2005	0.7995
08/01/95	3	5	1	0.253	0.747
08/01/95	3	8	1	0.4048	0.5952
08/02/95	3	5	0.75	0.253	0.497
08/02/95	1	5	0.75	0.199	0.551
08/02/95	2	5	0.75	0.2005	0.5495
08/02/95	4	4	0.75	0.1804	0.5696
08/02/95	4	6	0.75	0.2706	0.4794
08/02/95	4	6	0.75	0.2706	0.4794
08/02/95	4	6	0.75	0.2706	0.4794
08/02/95	4	6	0.75	0.2706	0.4794
08/03/95	4	6	0.75	0.2706	0.4794
08/03/95	4	6	0.75	0.2706	0.4794
08/03/95	1	5	0.75	0.199	0.551
08/03/95	1	5	0.75	0.199	0.551
08/03/95	1	5	0.75	0.199	0.551
08/03/95	1	5	0.75	0.199	0.551
08/03/95	2	5	0.75	0.2005	0.5495
08/03/95	2	5	0.75	0.2005	0.5495
08/04/95	2	5	0.75	0.2005	0.5495
08/04/95	2	5	0.75	0.2005	0.5495
08/04/95	3	5	0.75	0.253	0.497
08/04/95	3	5	0.75	0.253	0.497
08/04/95	3	5	0.75	0.253	0.497
08/04/95	3	5	0.75	0.253	0.497
08/07/95	5	5	0.75	0.2545	0.4955
08/07/95	5	5	0.75	0.2545	0.4955
08/07/95	5	5	0.75	0.2545	0.4955
08/07/95	5	5	0.75	0.2545	0.4955
08/07/95	6	4	0.75	0.3065	0.4435

Table 2: List of configurations tested. See previous table for identity of samples.

5 Results

5.1 Geometry Tests and Room Temperature Results

Initial studies were conducted at room temperature to determine the high field structure of the B-H curve and to perform tests with different configurations to confirm that geometric corrections for the ratio of pole tip gap to width are small. Since typical values of h_T are 0.5 inches and typical 'pole-tip' areas are 3" x 3" or 3" x 6", we expect that the field across the gap is uniform, so that the measurement against the top iron surface represents the field in the compensator very well. Results for these typical samples were obtained with a variety of stack heights and gaps to confirm the assumptions for the calculation. Figures 4, 5, 6 display these results. Note that these results are taken on a cycle in which the currents increase from the initial field produced by the remanent field of the dipole. Hysteretic effects are not large and have not been explored with this system.

For Sample 4 we have a less satisfactory geometry. With even 3 or 4 stacks side by side, we only achieve a 'pole-tip' width of 1.2 - 1.7 inches compared with h_T from 0.5 to 0.8 inches. Figure 7 shows that the agreement here is still sufficient to learn some information on the material but much less satisfactory than that achieved with the larger samples. While temperature dependant tests were being completed on other samples, a larger sample was obtained from Carpenter Technologies of Temperature Compensator 30 Type 4 material. Tests reported below use that material (Sample 5).

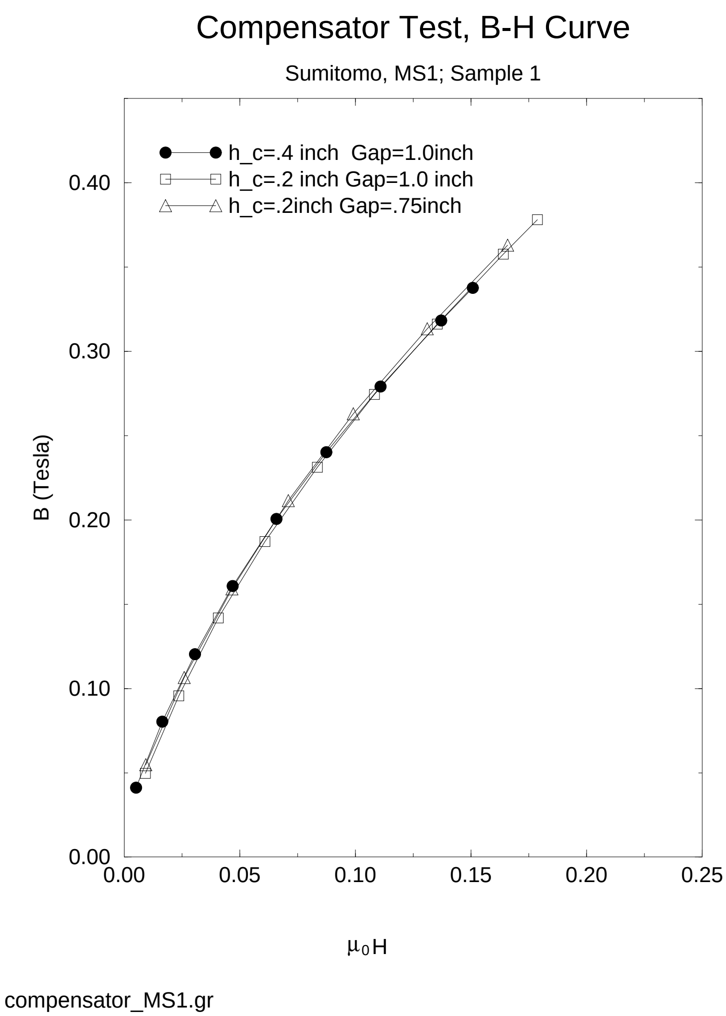


Figure 4: Room Temperature Measurements of B *vs.* H for Sumitomo MS1 compensator material with various geometries.

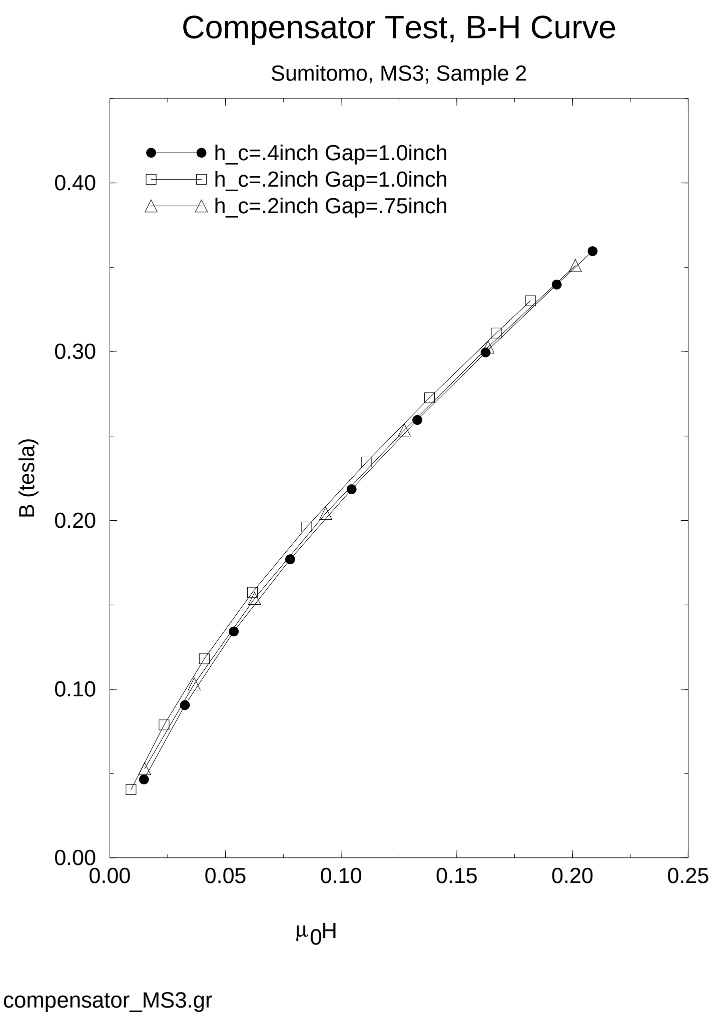
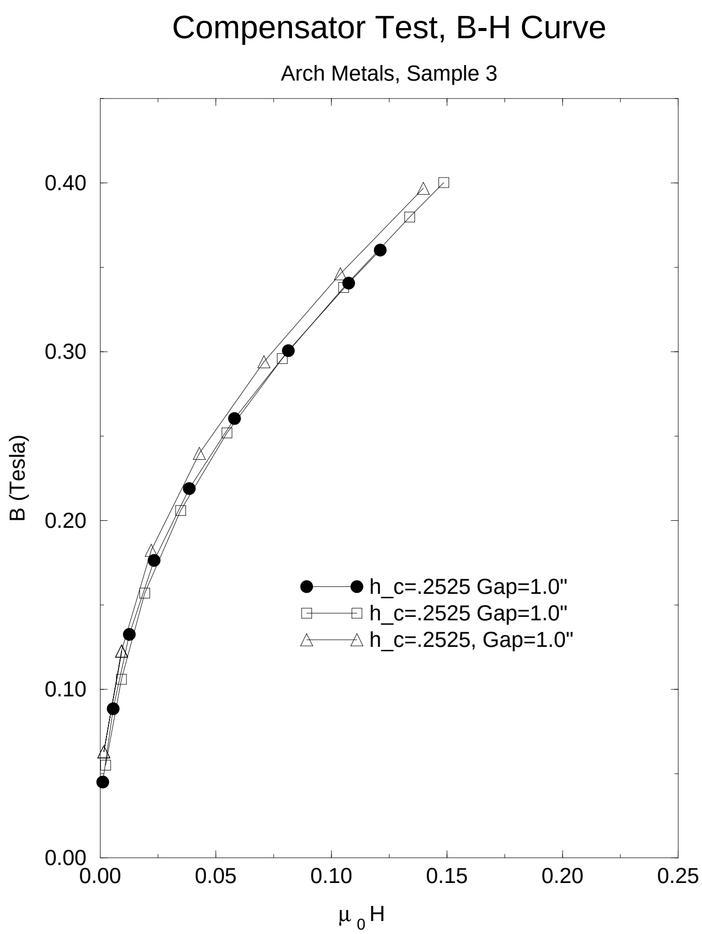
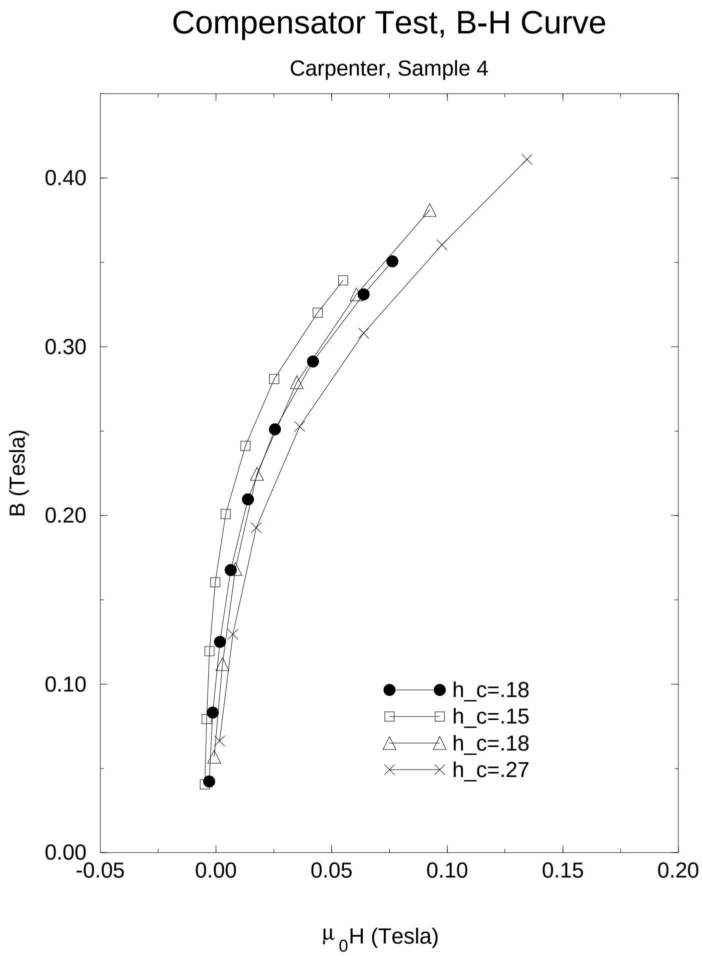


Figure 5: Room Temperature Measurements of B *vs.* H for Sumitomo MS3 compensator material with various geometries.



compensator_arch.gr

Figure 6: Room Temperature Measurements of B *vs.* H for Arch Metals compensator material with various geometries.



Compensator_carpenter.gr

Figure 7: Room Temperature Measurements of B *vs.* H for Sample 4 from Carpenter Technologies. Various geometries do not produce as good agreement here as with other samples. We attribute this to the poorer geometry for these tests.

5.2 Temperature Dependent B-H Measurements

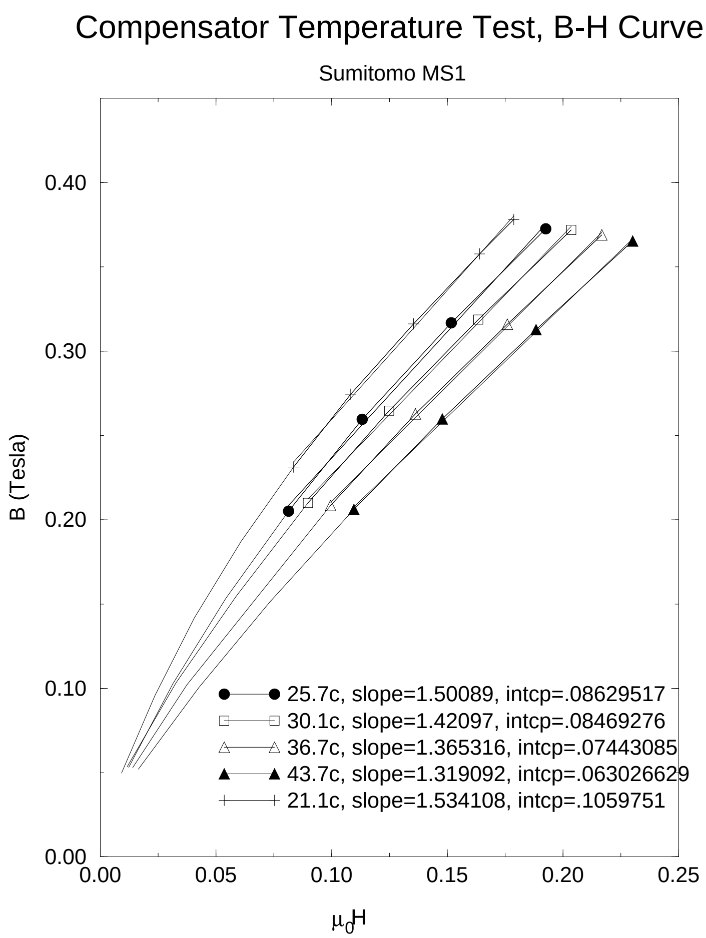
Having confirmed that the technique would provide useful measurements of the magnetic properties of the compensator, we proceeded to move on to measurements at various temperatures appropriate for the Recycler Ring project. By surrounding the iron box shown in Figure 1 with electrical heating tape and fiberglass insulation we have a variable temperature enclosure for measurements. An electrical temperature controller was used with a sensor unit attached between the box and the insulation. Temperature was measured with a platinum resistor whose resistance was monitored with an HP3457 DVM 4-wire resistance mode measurement and converted to temperature using the appropriate conversion standard. After selecting a target temperature, we heated slowly to it, achieving it within 0.1 K in a few minutes. We waited between 5 and 10 minutes additional to permit the entire sample to come to a uniform temperature. Measurements were then taken at intervals in current which permit the desired range of the B-H curve to be determined. Temperatures were constant to 0.1 K for all measurements at a given nominal temperature setting.

Figures 8, 9, 10, 11, and 12 show the results of these measurements. in each figure we show the measured points for each temperature as a solid line. A linear fit to selected points (identified with symbols) was performed to obtain an intercept (B_r) and a slope (μ) for each temperature. Note that, although this is a very good approximation for some curves, it is only adequate for others. Labels show the fitted values obtained. The intercept B_r is given in Tesla while the slope μ is dimensionless. The Fe-Ni alloys show useful compensation. We find the monel alloy is virtually non-magnetic; $mu \approx 1.05$ at all temperatures and excitations.

5.3 Fits to Temperature Dependance

Using the results from the data above, we plot in Figure 13 the fitted B_r *vs.* temperature. These results are quite linear for the Arch Metals and the Carpenter samples. For the Sumitomo MS1 sample, the nonlinearity may be just experimental limitations. The behavior of the MS3 sample suggests that we are approaching the Curie temperature of this material. This is consistent with the manufacturer's data. The results of the linear fit shown are tabulated in Table 3 with both the slope and the fitted value at $21^o\ C$ shown.

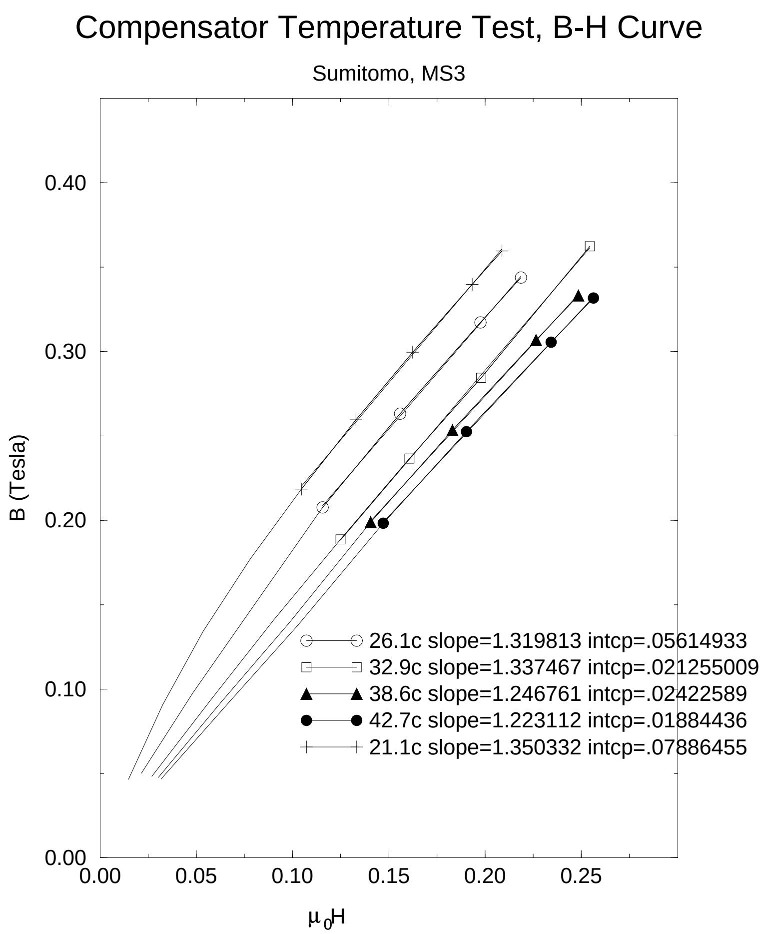
The Curie Law describes the ratio of the magnetization at the measured



compensator_MS1_temp_slope.gr

Figure 8: Temperature dependant measurements of B *vs.* H for Sumitomo MS1 compensator material.

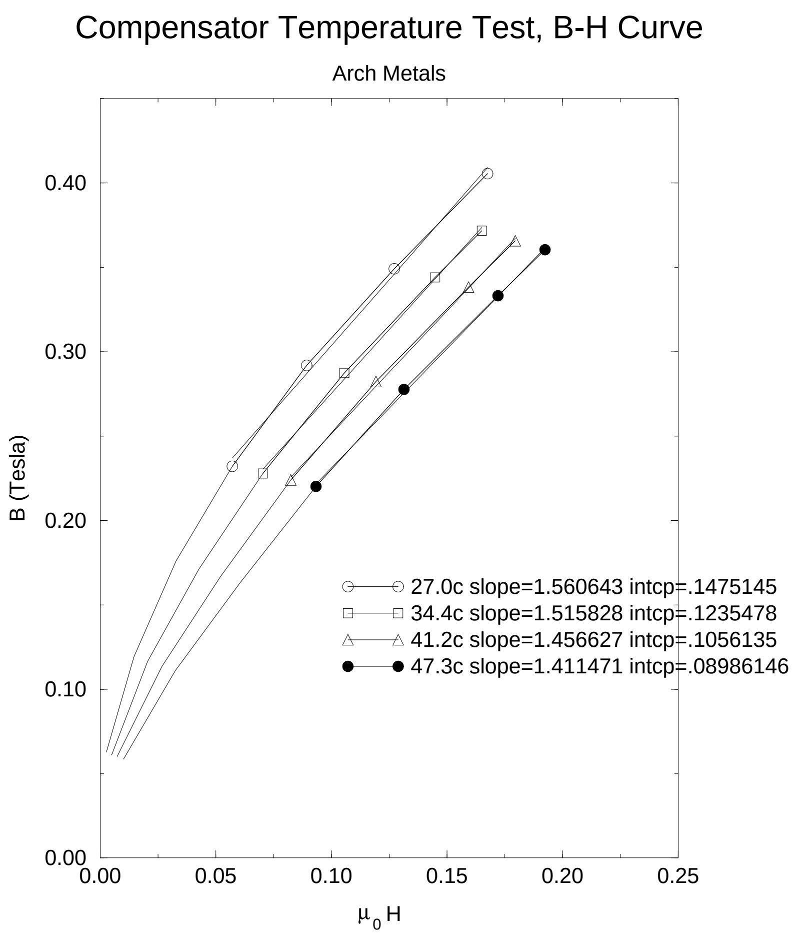
temperature to the magnetization at absolute zero. The point at which the magnetization disappears is called the Curie Temperature, θ_C. It is reported that the experimental data follow a Curie Law behavior at all points of the magnetization curve well above the 'knee'[3] where the differential μ drops from high values to values of only a few. This suggests that $\mu = dB/d\mu_0 H$ should be expected to be nearly independent of temperature in this region. In Figure 14 we plot the fitted values of the μ (slope) *vs.* temperature from



compensator_MS3_temp_slope.gr

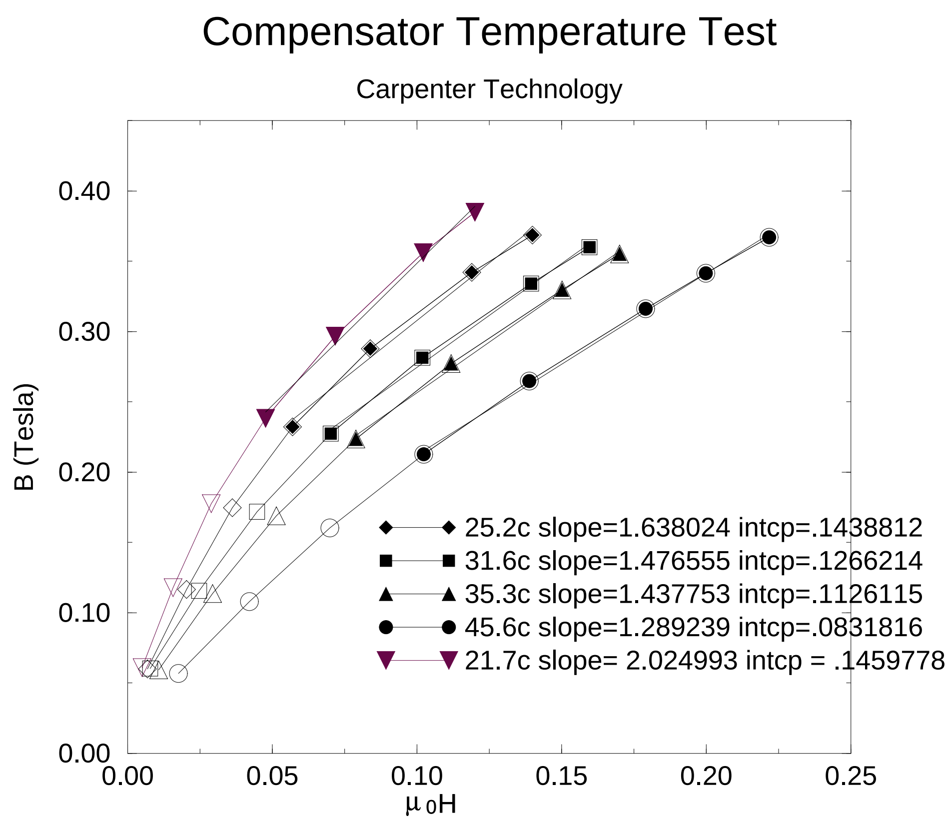
Figure 9: Temperature dependant measurements of B *vs.* H for Sumitomo MS3 compensator material.

the B-H measurement above. We see that the change in μ is small. The lines are linear fits to the data. Results are reported in Table 3.



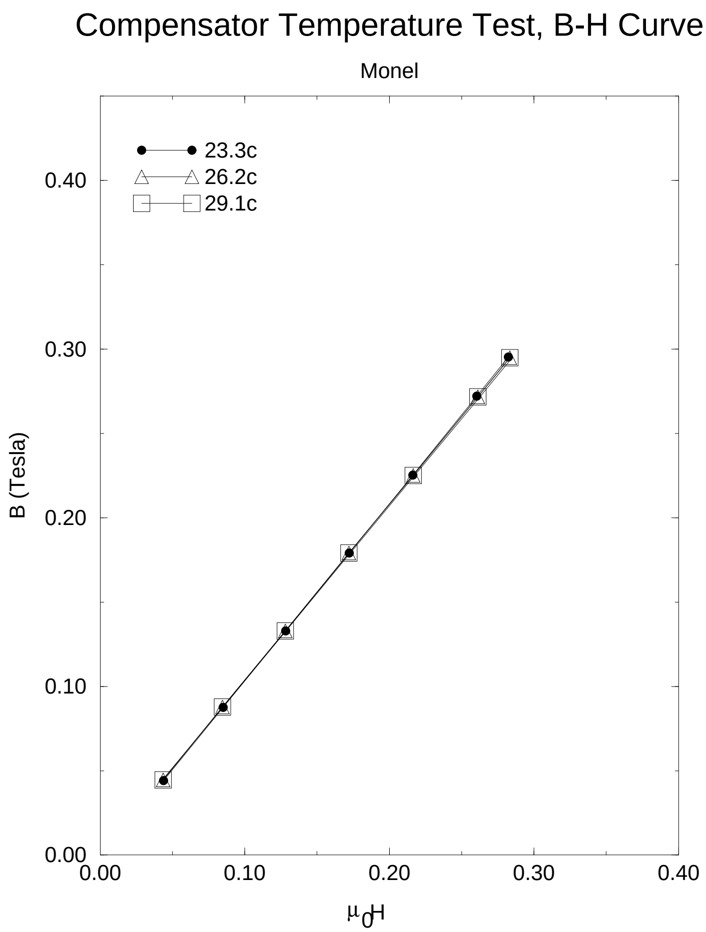
compensator_arch_temp_slope.gr

Figure 10: Temperature dependant measurements of B *vs.* H for Arch Metals compensator material.



compensator_carpenter_temp_slope.gr

Figure 11: Temperature dependant measurements of B *vs.* H for Carpenter Technologies Temperature Compensator 30 Type 4 material, Sample 5.



compensator_monel_temp.gr

Figure 12: Temperature dependant measurements of B *vs.* H for monel material.

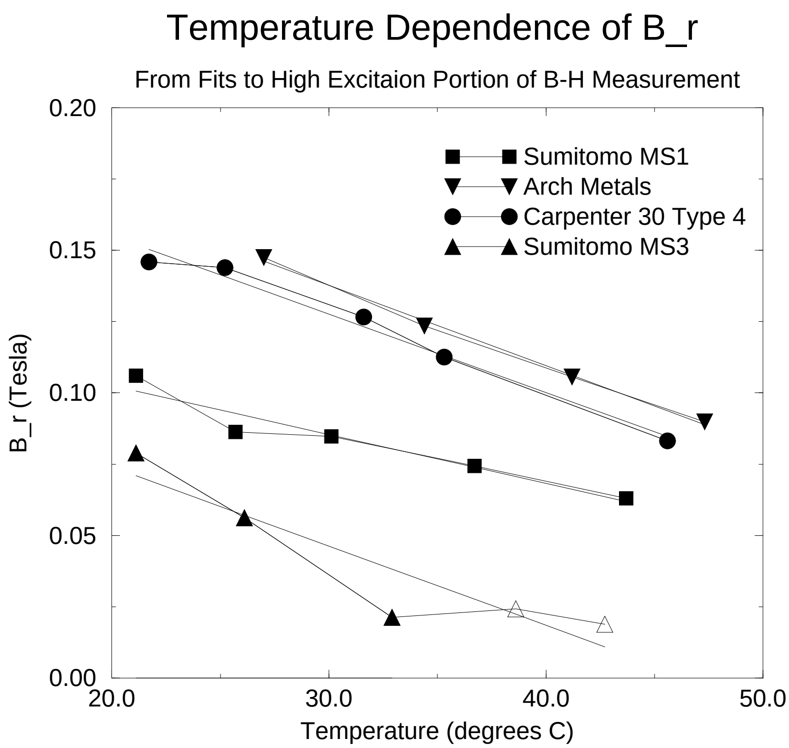


Figure 13: Fitted B_r *vs.* T for various compensator products. Note that this B_r results from a linear fit to high field B-H data, not the actual intercept at $H = 0$. The straight lines result from a linear fit to B_r *vs.* T of all points in each data set. Values from these fits are given in the table below. For Sumitomo MS3 material, a linear fit to the points with solid fill is given separately, recognizing the nearness of the Curie Temperature.

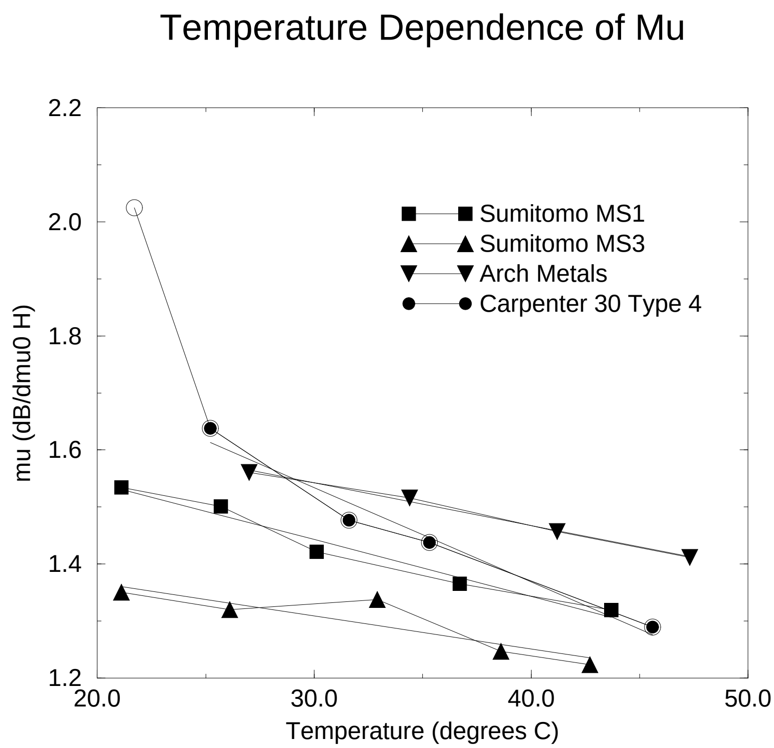


Figure 14: Fitted μ *vs.* T for various compensator products. Note that this μ results from a linear fit to high field data. It provides a value of $dB/d\mu_o H$ at high field (greater than 1 kOe). Linear fits to the filled points are shown and the values from these fits are given in the table below. Measurements of the room temperature data for the Carpenter material do not extend to sufficiently high fields to permit determination of a comparable μ value.

6 Summary and Conclusions

Material	B_r at 294 K Tesla	dB_r/dT Tesla/K	$1/B_r\ dB_r/dT$ 1/K	μ at 294 K	$d\mu/dT$ 1/K
MS1	0.1008	-1.717e-03	-1.702e-02	1.532	-0.0099
MS3	0.0712	-2.775e-03	-3.899e-02	1.361	-0.0058
MS3 ($< 33^oC$)	0.0800	-4.897e-03	-6.121e-02		
Arch	0.1632	-2.826e-03	-1.732e-02	1.609	-0.0075
Carpenter	0.1469	-3.003e-03	-2.044e-02	1.682	-0.0165

Table 3: Results from tests as fit. B_r and μ are reported at $21^o\ C$

The effort to provide temperature compensated magnets for the Recycler Ring requires data on the high field properties of temperature flux compensator materials to support engineering analysis of the magnet design. We have measured magnetic properties of a variety of magnetic temperature compensation materials as a function of temperature. In Table 3 we present a summary of our results. The fits used a linear regression in the XMGR program applied to the data as described in Figures 13 and 14. Since the Curie Temperature for MS3 material is so close to our operating range, we have fit both the whole sample and the 3 points which appear to fall in the linear portion of the curve. We note that the range over which the B-H curves have been fitted is not held constant when doing the linear fits, resulting in uncertainties in the fitted results beyond that inherent in the measured B-H curves. This is especially noteworthy in the room temperature measurements of the Carpenter material.

These measurements provide evidence that the B-H curve for this material is well represented in the range near 1500 Oe by a linear fit to μ and B_r. The measurement method has been confirmed using data with different geometries. There are some discrepancies which cause concern. The data shown in Figures 14 and 11 do not agree, although they are supposed to be the same product from Carpenter Technologies. Additionally, Measurements at Fermilab with an Epstein frame and the product data sheets from Carpenter Technologies both suggest that for $H = 50 - 100\,Oe$ one should expect B to be larger than shown in Figure 11. Both resolution and geometry issues are more critical in this part of our data but we nevertheless do not understand the discrepancies. We expect to take additional data to provide more understanding. New measurements should extend to higher fields using probes which were not available when this data was taken.

Calculations of the response expected from the magnets we are building utilize the values of $B_r, dB_r/dT$, and μ. The calculations suggest that the area of compensator material required is governed by the value of dB_r/dT while the amount of flux lost to the compensator is governed by $1/B_r\ dB_r/dT$. We also observe that if the material obeys a Curie Law for the B_r then the value of $1/B_r\ dB_r/dT$ should be predicted by the reported Curie temperature for the material. These studies will be supplemented with low field measurements using an Epstein Frame and additional measurements as other samples become available.

7 Acknowledgements

We thank Dean Validis for assembling the mechanical apparatus for this test and Dan Massengill for assistance in assembling the temperature tape, controller and insulation system. Linda Alsip guided the procurement of materials and certifications of their properties.

References

[1] K. Bertsche, J. F. Ostiguy, and G. W. Foster. Temperature Considerations in the Design of a Permanent Magnet Storage Ring. In *Proceedings of the 1995 IEEE Particle Accelerator Conference, Dallas, May 1-5, 1995*, page 1381. Institute of Electrical and Electronic Engineers, 1995.

[2] I. F. Kinnard and H. T. Faus. A Self-Compensating Temperature Indicator. *Trans. Am. Institute of Electrical Engineers*, 49:949, 1930.

[3] L. R. Jackson and H. W. Russell. Temperature-sensitive Magnetic Alloys and Their Uses. *Instruments*, 11:280, 1938.